REPORT 62

NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AERONAUTICAL RESEARCH AND DEVELOPMENT

SOME CORRELATIONS OF FLIGHT-MEASURED AND WIND-TUNNEL MEASURED STABILITY AND CONTROL CHARACTERISTICS OF HIGH-SPEED AIRPLANES

by

Walter C. Williams, Hubert M. Drake and Jack Fischel

This Report was presented at the Ninth Meeting of the Wind Tunnel and Model Testing Panel, held from 27th to 31st August, 1956, in Brussels, Belgium.

SUMMARY

Comparisons of wind-tunnel and flight-measured values of stability and control characteristics are of considerable interest to the designer, since the wind-tunnel method of testing is one of the prime sources upon which estimates of the characteristics of a new configuration are based. In this paper comparisons are made of some of the more important stability and control characteristics of three swept-wing airplanes as measured in flight and in wind tunnels. Wind-tunnel data are used from high-speed closed-throat tunnels, a slotted-throat transonic tunnel, and a supersonic tunnel.

The comparison shows that, generally speaking, the wind tunnels predict all trends of characteristics reasonably well. There are, however, differences in exact values of parameters, which could be attributed somewhat to differences in the model caused by the method of support. The small size of the models may have some effect on measurements of flap effectiveness. When non-linearities in derivatives occur during wind-tunnel tests, additional data should be obtained in the region of the non-linearities. Also, non-linearities in static derivatives must be analyzed on the basis of dynamic motions of the airplane. Aeroelastic corrections must be made to the wind-tunnel data for models of airplanes which have thin surfaces and are to be flown at high dynamic pressures. Inlet effects can exert an influence on the characteristics, depending upon air requirements of the engine and location of the inlets.

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SOMMAIRE

La comparaison des qualités de stabilité et de contrôle démontrées au cours d'expériences en souffleries d'une part, au cours d'essais en vol d'autre part, présente pour l'engénieur un intérêt considérable, car les méthodes d'expérimentation en souffleries fournissent les données principales sur lesquelles on se base pour juger des propriétés d'un nouveau modèle. Au cours de cet exposé, l'auteur établit des comparaisons entre les résultats obtenus en vol et en souffleries en ce qui concerne certaines qualités de stabilité et de contrôle parmi les plus importantes, de trois avions à ailes en flèche. Les données obtenues en souffleries résultent d'expériences effectuées dans des souffleries à grande vitesse et à veine fermée, dans une soufflerie transsonique à veine perforée, et dans une soufflerie supersonique.

Les comparaisons établies montrent que, en règle générale, les expériences effectuées en souffleries mettent assez bien en évidence toutes les tendances dans le comportement des appareils. On observe cependant, dans les valeurs exactes des paramètres, des différences que l'on peut attribuer dans une certaine mesure aux méthodes de montage des maquettes. La taille réduite des maquettes peut influer sur les mesures de l'efficacité des volets. Lorsque, au cours d'expériences en souffleries, les dérivées deviennent non-linéaires, on devrait obtenir des données additionnelles dans la région où les dérivées cessent d'être linéaires. De même, lorsque les dérivées statiques deviennent non-linéaires, ce phénomène doit être analysé sur la base des déplacements dynamiques de l'avion. On doit apporter aux données fournies par les expériences en souffleries des corrections concernant l'aéroélasticité, lorsqu'il s'agit de maquettes d'avions à surfaces minces devant voler à de hautes pressions dynamiques. Les effets dûs aux admissions d'air peuvent également exercer une influence sur les propriétés de l'appareil, influence qui dépend des besoins en air du moteur et de l'emplacement des admissions.

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NOTATION

C_m	pitching-moment coefficient
$C_{m_{C_L}}$	static margin, percent mean aerodynamic chord
$\Delta C_{m_{C_L}}$	$\left(C_{m_{C_L}}\right)_{WT} - \left(C_{m_{C_L}}\right)_F$
$C_{m_{i_t}}$	pitching-moment coefficient due to stabilizer deflection, per degree
C_N	normal-force coefficient
C_{N_α}	normal-force-curve slope, per degree
C_{n_β}	directional stability parameter, per degree
i_t	stabilizer angle, negative when stabilizer leading edge down, degrees
Δi_t	$\left(i_t\right)_{WT} - \left(i_t\right)_F$
M	Mach number
$\frac{pb}{2V}/\delta$	wing-tip helix angle per degree aileron deflection, radians/degree
q_t/q	dynamic pressure ratio at tail
α	angle of attack, degrees
$d\epsilon/d\alpha$	variation of downwash angle with angle of attack
τ	relative elevator stabilizer effectiveness
ϵ	angle of downwash at the horizontal tail, degrees
q_t	dynamic pressure at the horizontal tail, lb/sq ft
q	dynamic pressure, lb/sq ft
p	rolling velocity, radians/sec
b	wing span, ft
v	true airspeed, ft/sec
δ	aileron deflection in degrees

Subscripts: F flight WT wind tunnel

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1. INTRODUCTION

One of the principal tools of the aircraft designer in predicting the stability and control characteristics of a new airplane is the use of models tested in wind tunnels. There is, of course, the question whether the model results accurately predict, in full flight, characteristics of the airplane in free flight or, in other words, the degree of correlation between the two results. This problem has received considerable attention. Most of this work (Reference 1 for example) has been performed at subsonic speeds and indicates that, in general, good correlation can be obtained when the model accurately represents the actual aircraft, and the tests, both flight and wind tunnel, are carefully performed.

Some work has been reported on the correlation between the wind-tunnel and flight-measured stability characteristics in the transonic speed regime[2]. Correlations of transonic and supersonic results are currently of particular interest in view of the availability of wind tunnels capable of testing through the transonic speed range. Problems of correlations in this speed range are complicated by the compromises imposed on the model by the mounting system, stings for example, where the aft end of the fuselage must be altered to accommodate the sting. It is also necessary to utilize much smaller models than were possible in the low-speed tunnels. The purpose of this paper is to present some correlations of flight-measured and wind-tunnel measured stability and control characteristics of high-speed airplanes.

2. AIRPLANES AND TESTS

Three-swept-wing airplanes are considered in this study. All are single-engine, fighter-size airplanes with a sweep range from 35° to 60°. Much of the flight data were obtained at an altitude of 40,000 ft with some of the supersonic data extending to altitudes as high as 60,000 ft. The overall Reynolds number variation was from 8 million to 19.5 million. The flight data were obtained with power on, for the most part between 90% and 100% available thrust.

The wind-tunnel tests for these airplanes were performed in the following NACA wind tunnels:

Langley 8 ft transonic tunnel
Langley 8 ft high-speed tunnel
Langley high-speed 7 ft × 10 ft tunnel
Langley 4 ft × 4 ft supersonic pressure tunnel.

**High-Speed Flight Station, N.A.C.A., Edwards, California, U.S.A.*

All models were sting supported and the forces were measured by internally mounted strain-gage balances. The Reynolds numbers of the test varied from 1.9 million to 3.6 million. The model tests were made with no-power simulation and the inlets were faired except for airplane A which employed an open duct. There were differences between the models and the actual airplanes in most cases. In general, these differences and the model scales are as follows:

Airplane A, 1/11 scale model:
8 ft transonic tunnel tests
High-speed 7 ft × 10 ft wind tunnel.

1. The wind-tunnel model incorporated an enlarged aft fuselage accept the sting support.
2. The wind-tunnel model exposed-horizontal-tail area was maintained, which resulted in increased tail span.

These differences are shown in Figure 1.

Airplane B, 1/16 scale model:
8 ft closed-throat tunnel
8 ft transonic tunnel
7 ft × 10 ft closed-throat tunnel
4 ft × 4 ft supersonic pressure tunnel.

1. The wind-tunnel model incorporated an enlarged aft fuselage to accommodate the sting support.
2. The wind-tunnel model incorporated constant-percentage-chord wing sections compared with similar root sections but thicker tip sections on the airplane wing. In addition, during the 8 ft closed-throat tunnel and 4 ft × 4 ft supersonic pressure tunnel tests, the model was tested without a cockpit canopy.

Airplane C, 1/14 scale model:
8 ft transonic tunnel
4 ft × 4 ft supersonic tunnel.

3. RESULTS AND DISCUSSION

One of the prime considerations in the measurement of airplane characteristics is the lift-curve slope of the airplane. A comparison of the variation of normal-force coefficient with angle of attack, for airplane A as measured in flight and in the 8 ft transonic tunnel at Mach numbers of 0.76 and 0.91, is shown in the upper part of Figure 2. The data are for trimmed conditions. As can be seen in this figure, the correlation is reasonably good in the linear range. At angles of attack above peak lift or above the break in the curve, indicative of separated flow, there are discrepancies. The lower portion of this figure shows the variation with Mach number of the ratio of flight-determined to wind-tunnel-determined normal-force-coefficient slope for airplanes A and B. These slopes were taken at about the normal-force coefficient for level flight. As can be seen, the results are within 10% of each other, with the flight-measured values being generally higher. The transonic data up to $M = 1.15$ were obtained from the 8 ft transonic tunnel, the data at $M = 1.2$ from the 8 ft high-speed tunnel, and the higher Mach number data were obtained from the 4 ft × 4 ft supersonic pressure tunnel.

Determination of the static margin is important in establishing the necessary center-of-gravity position for a configuration. The variation of static margin with Mach number is shown in Figure 3 for airplane A, as measured in the 8 ft transonic wind tunnel, and as measured in flight from pulse disturbances. The data are referenced to the same center-of-gravity position. This figure shows that similar variations with Mach number are exhibited in the two sets of data. The flight data, however, show a consistently higher value of static margin by about 3%. It is felt that differences between the model and airplane in the aft fuselage and horizontal-tail configurations (Fig. 1) could account for these discrepancies. The lower part of this figure shows the incremental difference in static margin between the data from the two test mediums for airplanes A and B at normal-force coefficients for level flights. As stated previously, the data for airplane A exhibit a constant difference of about 3%. The flight values for airplane B are about 5% higher than the data from the closed-throat tunnel up to a Mach number of about 0.85. Above this Mach number the difference decreases, and at a Mach number of about 0.95 the wind-tunnel data show about 5% greater static margin than that shown by the flight tests. This variation between Mach numbers of 0.85 and 0.95 is felt to be caused by choking effects in the closed-throat tunnel. The results from the slotted-throat tunnel are similar to those from the closed-throat tunnel up to a Mach number of 0.85. Above this Mach number the difference varies somewhat, but throughout the Mach number range the flight data show higher static margins by from 1 to 5%. The supersonic data for airplane B show similar increments in static margin. In this case, however, because of high stability levels, larger errors can be tolerated.

In addition to checking the levels of stability, it is important with high-speed configurations to establish the variations of stability with angle of attack in order to explore for the existence of non-linearities which may lead to an undesirable characteristic, such as pitch-up. Typical variations of pitching moment, with angle of attack for airplane A, as measured in flight and in the 8 ft transonic tunnel at Mach numbers of 0.76 and 0.91, are shown in Figure 4. The flight data for the wing-fuselage pitching-moment coefficient (tail off) were obtained from measurements of horizontal-tail loads. The overall airplane pitching-moment coefficient was obtained from flight-measured variations of stabilizer angle with angle of attack corrected for pitching acceleration effects. In making these calculations, it was assumed that pitching-moment coefficient due to stabilizer deflection C_{mi_t} was constant, q_t/q was equal to unity, and that the downwash $d\epsilon/d\alpha$ was constant. The data show that the pitching-moment curves are generally similar. At both Mach numbers the comparison yielded a difference in the angle of attack for trim. At a Mach number of 0.76, however, the non-linearities occur in the tunnel data at lower angles of attack, and the data do not exhibit the large dip in the curve that is shown for the flight results. This difference could possibly be accounted for by the lack of sufficient wind-tunnel test points to define such a variation. The data at a Mach number of 0.91 are considered to be reasonably similar, both tail off and tail on. It should be pointed out that inspection of the shape of the pitching-moment curves is not sufficient to determine whether or not a pitch-up problem exists. It has been found that pitch-up can be a problem even with airplanes having neutral stability or even lightly positive stability in the non-linear region. The degree of stability above the pitch-up is also important. To evaluate pitch-up, it is necessary to make calculations of the motions of the airplane in dynamic manuevers using assumed arbitrary pilot control inputs. It is felt that these wind-tunnel data represent the flight case close enough for such calculations to be of value in predicting the maneuvering characteristics of the airplane.

Another important longitudinal characteristic is the variation with Mach number of the longitudinal control deflection required for level flight. Data of this type are shown in Figure 5. The upper portion of the figure shows the variation with Mach number of the stabilizer deflection for trim for airplane A as measured in flight and in the 8 ft transonic tunnel. As can be seen, the variations are generally similar for the two tests, with flight-measured data showing a large change in stabilizer deflection required above a Mach number of 0.90 than shown by the wind-tunnel data. In the lower portion of the figure where the difference between flight and wind-tunnel measurement is shown for airplanes A and B, it can be seen that the difference between flight and wind-tunnel trim values exceeds 1° of stabilizer travel only at a Mach number of 0.98 for airplane A. Over most of the range there is less than 0.5° difference in stabilizer deflection required for trim.

Although elevator control on high-speed airplanes is being replaced by all-movable or one-piece horizontal tails, it appears that flap-type rudders and ailerons may continue to be used. Some comparisons of measured values of elevator effectiveness are shown in Figure 6. The upper portion of this figure compares the variations of elevator effectiveness τ with Mach number as measured in flight and wind tunnel. This figure shows that there is an appreciable difference between the flight and wind-tunnel data, particularly above a Mach number of 0.9 where a much larger decrease in elevator effectiveness was measured in flight than in the wind tunnel. Data are shown in the lower part of Figure 6 on the basis of the ratio of flight-measured to wind-tunnel-measured values of τ for airplanes A and B. Although the lower speed values, below a Mach number of 0.8, are within 10%, the differences in transonic values are as high as ±25%. Somewhat better agreement is shown for the supersonic data then for the transonic data. At a Mach number of 1.6 the data are in perfect agreement, which may be fortuitous. The small size of elevators used on models such as these make the measurement difficult.

Additional flap-effectiveness data are shown in Figure 7, in which some aileron effectiveness information for airplane B is shown. In the upper part of this figure the ratio of flight-measured to wind-tunnel-measured values of $(pb/2v)/\delta$ is shown as a function of Mach number. The flight-measured values are generally lower than the wind-tunnel values, reaching only 70% of the wind-tunnel values at Mach numbers above 0.90. This difference is understandable when it is considered that the wind-tunnel data were obtained under non-rolling conditions assuming freedom in roll only, whereas the flight data were obtained in rudder-fixed aileron rolls where the airplane was free to yaw and pitch, as well as to roll. It is felt that aeroelasticity was not an important factor in this difference because the flight-test results did not show a significant effect of dynamic pressure within the range tested. The lower portion of this figure shows the variation of aileron effectiveness with Mach number for the two tests with the data normalized to the value of effectiveness existing at $M = 0.6$. These data show that if the level of effectiveness could be accurately established, the wind-tunnel tests would predict quite well the variation of aileron effectiveness with Mach number.

Static directional stability of a new configuration is of importance to the designer since it is one of the more important parameters in determining airplane behavior under dynamic as well as static lateral conditions. It has been found that many of the high-speed configurations exhibit large changes in directional stability with angle of attack. Typical data for airplane A are shown in the upper portion of Figure 8 where the static directional stability C_{n_β} is plotted as a function of angle of attack.

These data were obtained in the 7 ft x 10 ft wind tunnel at a Mach number of 0.70. There are no comparable flight data for this case because of the difficulty of measurement in flight. As can be seen in this figure, the directional stability becomes zero at an angle of attack of about 18°. From data such as these the variation with Mach number of the angle of attack at which the directional stability is zero was determined. This boundary is plotted on the lower portion of this figure. Also shown are points which represent the combinations of angle of attack and Mach number at which directional divergences have occurred in flight. It should be noted that, for any given Mach number, divergences occurred at angles of attack both less than and greater than that required for zero directional stability. It appears that, as in the case of pitch-up, dynamic analysis of the airplane motions is required in order to assess the problem.

Another variation of directional stability of concern to designers is that which occurs with changes in Mach number. Figure 9 relates the variation of directional stability with Mach number as measured in the wind tunnel to that measured in flight for airplane C. As can be seen, there are large discrepancies between the basic wind-tunnel data and the flight values. In the previous cases shown, relatively thick airfoil sections were used on the empennage and the dyanmic pressure for the tests was relatively low, less than 400 lb/ft^2. In the present case the vertical-tail thickness was about half that of the other airplanes and the maximum dynamic pressure was of the order of 850 lb/ft^2. Aeroelastic effects were found to be of importance. When the wind-tunnel data were corrected for aeroelastic effects, bending and twisting of the vertical tail, the agreement between the two sources was considerably better. This airplane has a relatively large jet engine, and when corrections were made for inlet effects (essentially, the energy required to turn the air into the inlet) the data were then found to agree within 10% throughout the Mach number range.

CONCLUDING REMARKS

Comparisons of wind-tunnel and flight-measured stability and control characteristics showed that the wind-tunnel data predicted all trends of characteristics reasonably well. Discrepancies were found in exact values, which may be attributed to differences in the models caused by mounting considerations and, in the case of flap effectivenesses, to the small size of the models. Where non-linearities in derivatives occur during wind-tunnel testing, it may be necessary to run additional points in the region of the non-linearities. Non-linearities in static derivatives should be analyzed under dynamic conditions. Aeroelasticity must be considered when dealing with thin airfoils and high dyanmic pressures. Inlet effects can be appreciable, depending on the size of the engine and the location of the inlets.

REFERENCES

1. Kayten, Gerald G. Koven, William — *Comparison of Wind-Tunnel and Flight Measurements of Stability and Control Characteristics of a Douglas A-26 Airplane.* NACA Rep. 816, 1945.

2. Duddy, R. R. — *Some Comparisons Between Wind Tunnel Model and Flight Test Results on Aircraft at High Angles of Attack.* (Presented at Ottawa AGARD Conference, June 1955). A.G.A.R.D. AG18/P8.

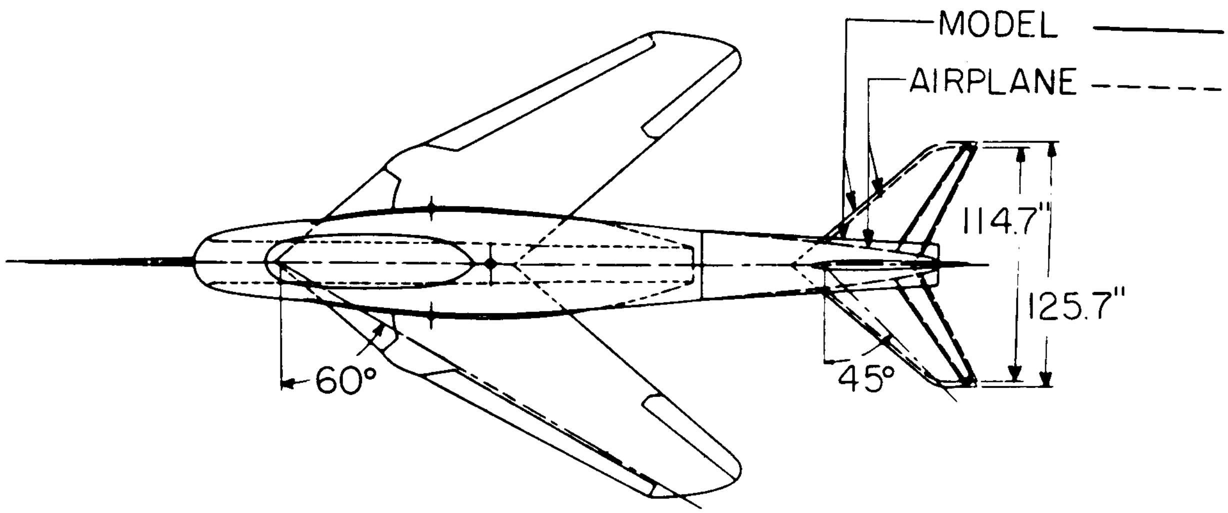

Fig. 1 Plan Form of Airplane A

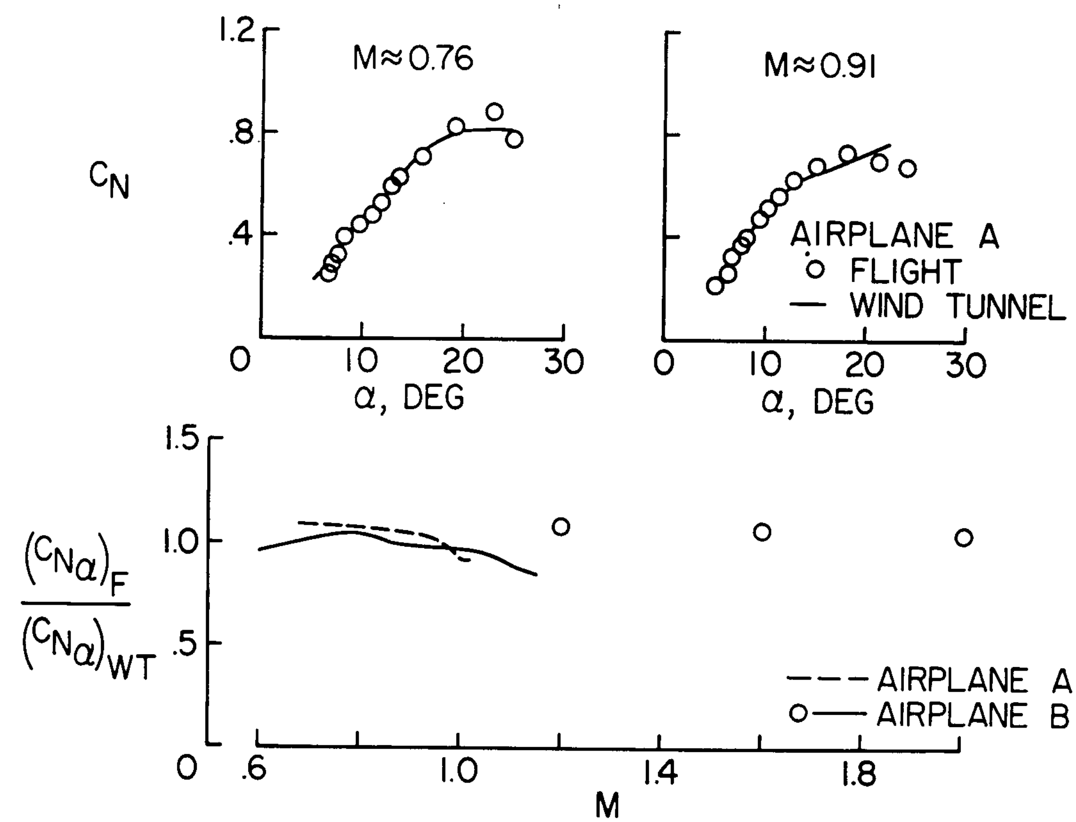

Fig. 2 Correlation of Flight and Wind-Tunnel Lift Characteristics for Airplanes A and B

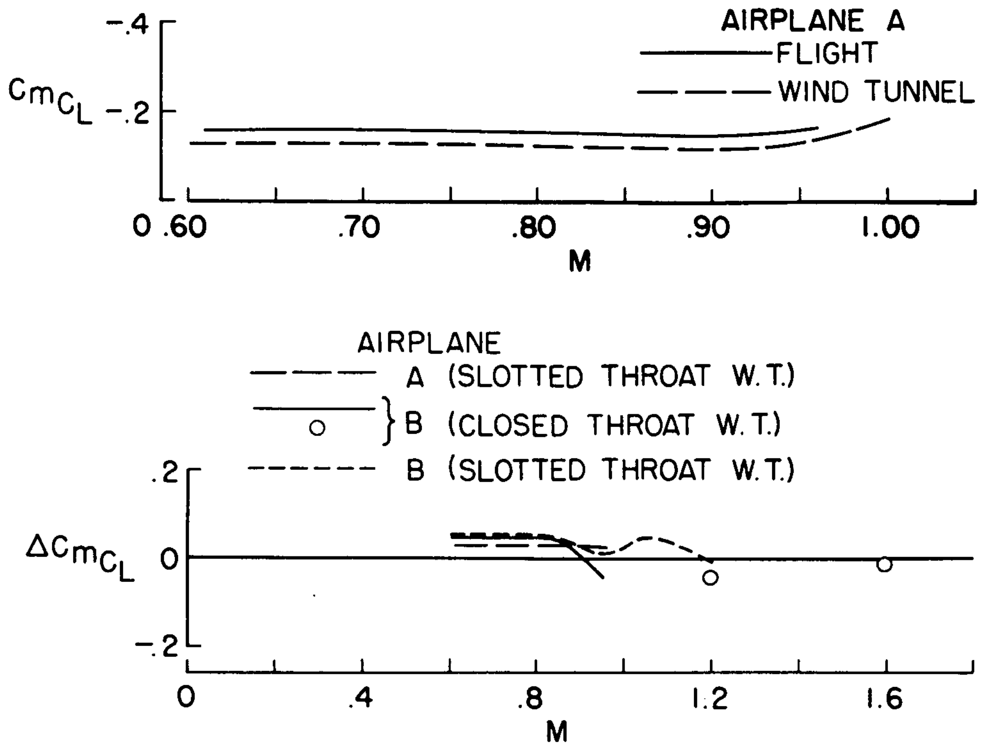

Fig.3 Comparison of Static Margin Determined in Flight and Wind-Tunnel Tests for Airplanes A and B

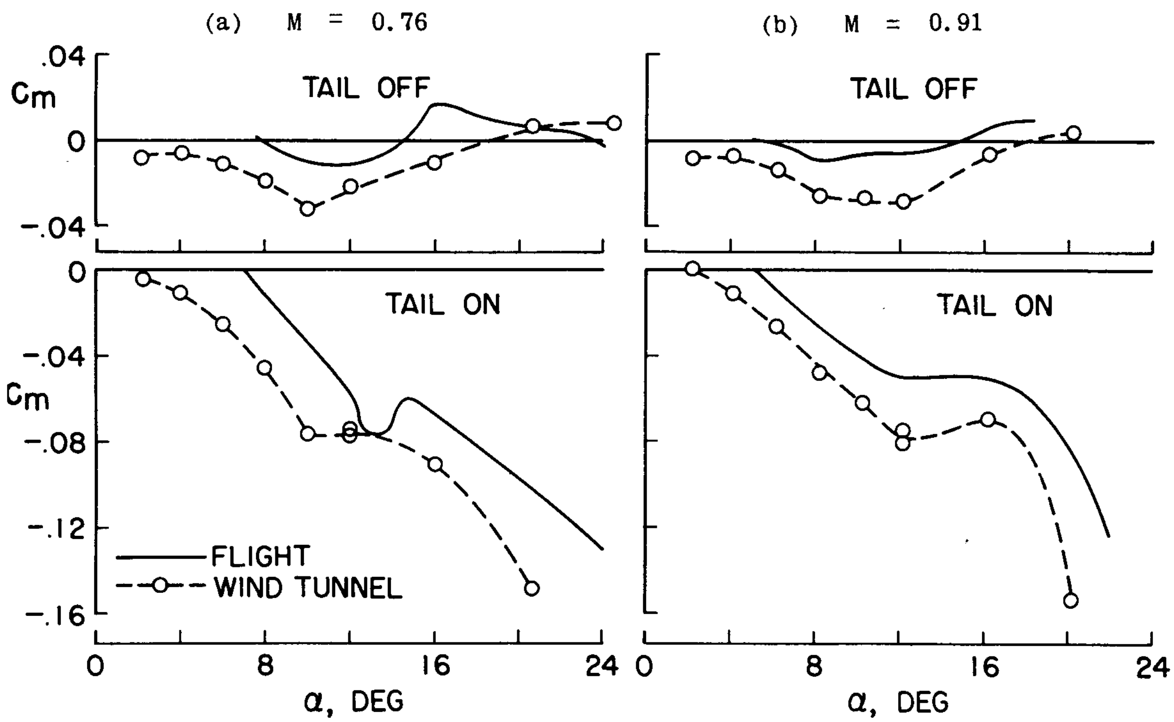

Fig.4 Flight and Wind-Tunnel Pitching-Moment Characteristics for Airplane A with and without Horizontal Tail

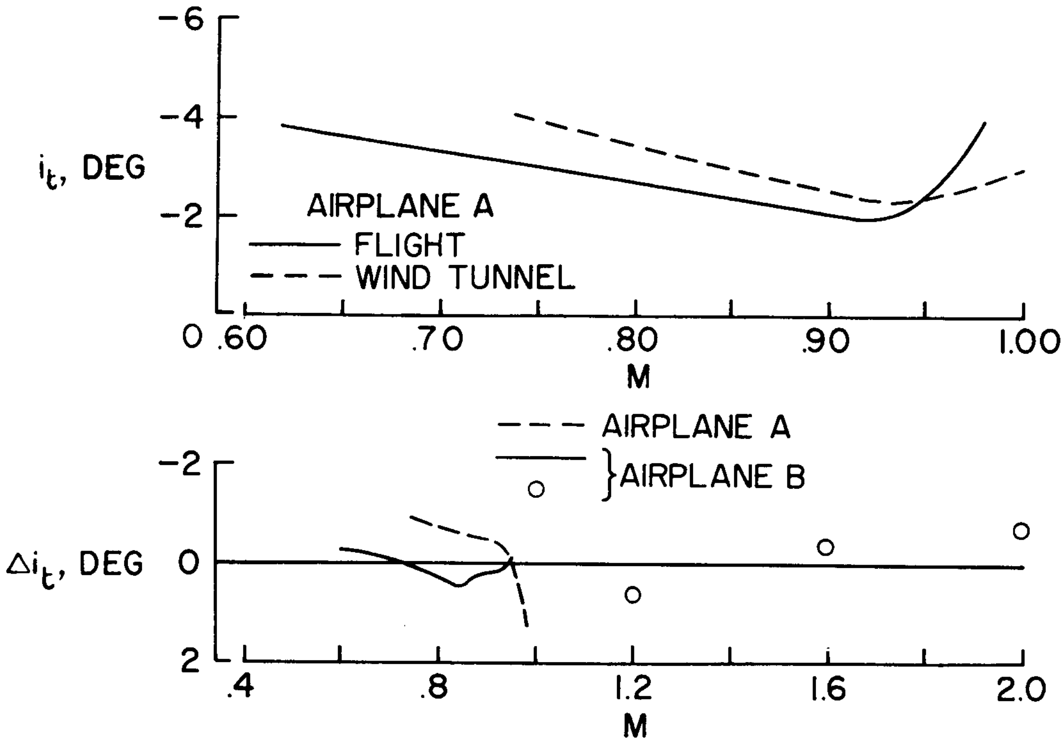

Fig.5 Trim Characteristics Determined in Flight and Wind-Tunnel Tests for Airplanes A and B

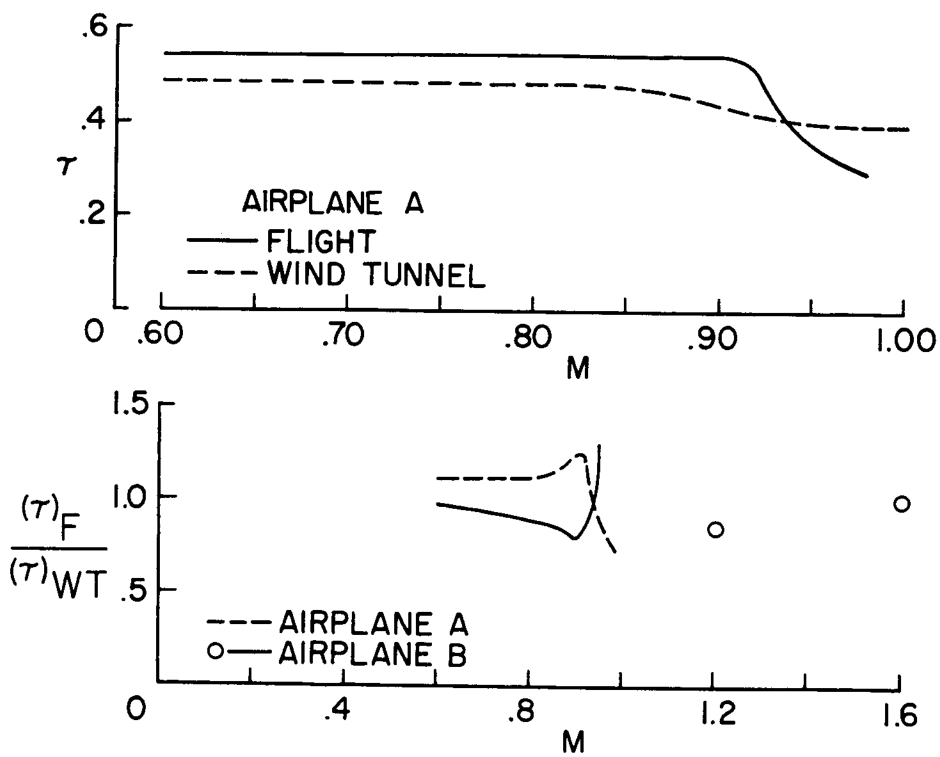

Fig.6 Relative Elevator-Stabilizer Effectiveness Determined in Flight and Wind-Tunnel Tests for Airplanes A and B

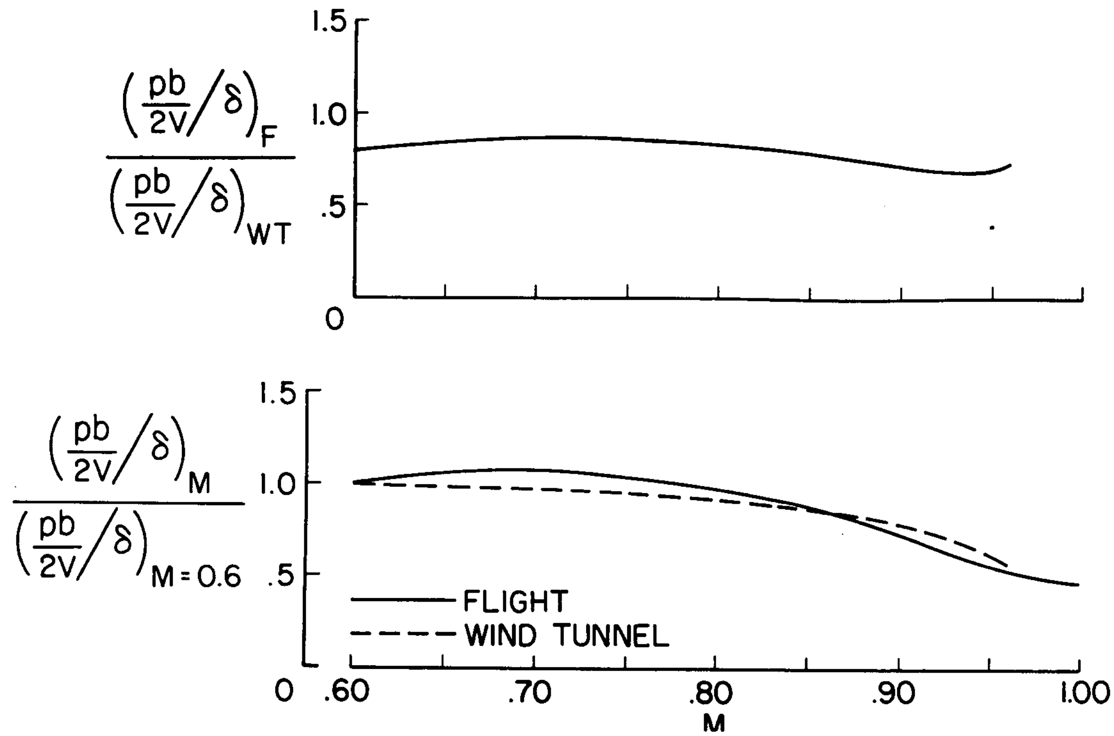

Fig. 7 Aileron Effectiveness Characteristics Determined in Flight and Wind-Tunnel for Airplane B

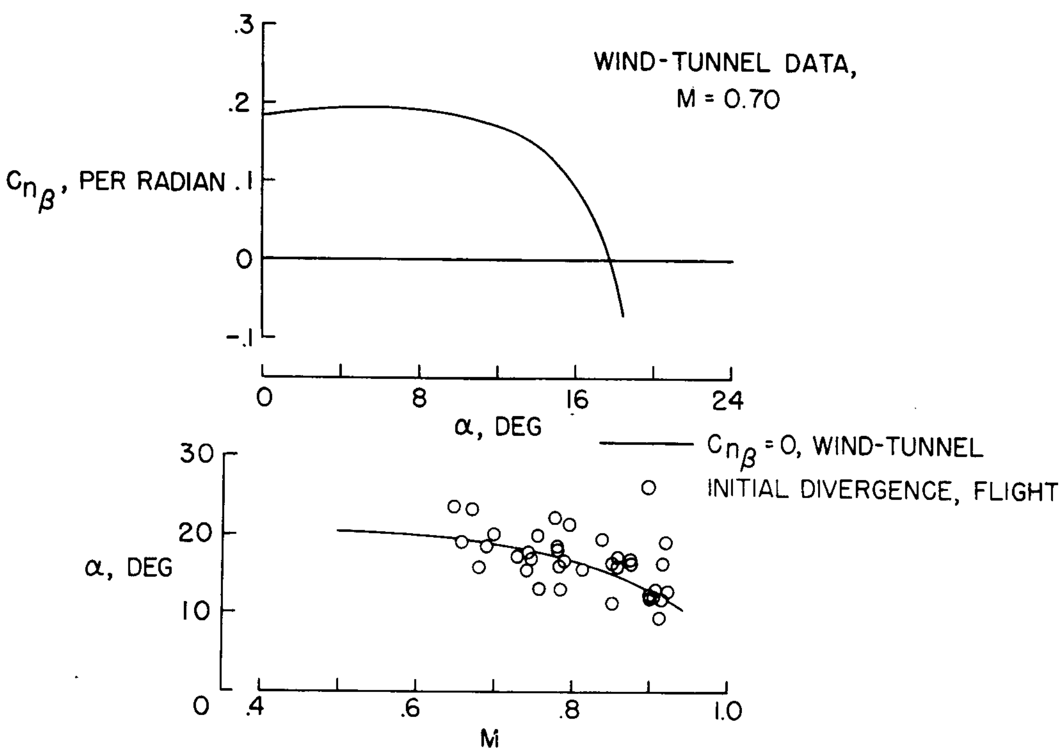

Fig. 8 Comparison of Flight and Wind-Tunnel Directional-Instability Characteristics for Airplane A

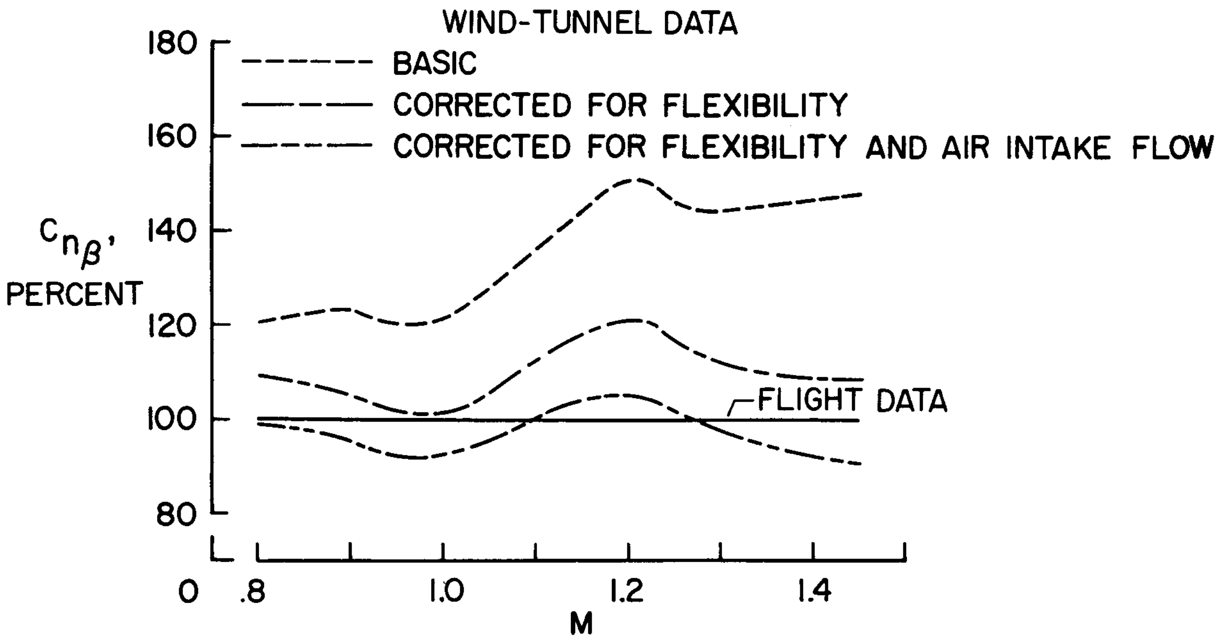

Fig. 9 Comparison of Flight and Wind-Tunnel Directional-Stability Characteristics for Airplane C

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